

# FINAL FATES OF ROTATING WHITE DWARFS AND THEIR COMPANIONS IN THE SINGLE DEGENERATE MODEL OF TYPE Ia SUPERNOVAE

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## ABSTRACT

Taking into account the rotation of mass-accreting white dwarfs (WDs) whose masses exceed the Chandrasekhar mass, we extend our new single degenerate model for the progenitors of Type Ia supernovae (SNe Ia), accounting for two types of binary systems, those with a main sequence companion and those with a red-giant (RG) companion. We present a mass distribution of WDs exploding as SNe Ia, where the WD mass ranges from  $1.38 M_{\odot}$  to  $2.3 M_{\odot}$ . These progenitor models are assigned to various types of SNe Ia. A lower mass range of WDs ( $1.38 M_{\odot} < M_{\text{WD}} \lesssim 1.5 M_{\odot}$ ), which are supported by rigid rotation, correspond to normal SNe Ia. A variety of spin-down time may lead to a variation of brightness. A higher mass range of WDs ( $M_{\text{WD}} \gtrsim 1.5 M_{\odot}$ ), which are supported by differential rotation, correspond to brighter SNe Ia such as SN 1991T. In this case, a variety of the WD mass may lead to a variation of brightness. We also show the evolutionary states of the companion stars at SN Ia explosions and pose constraints on the unseen companions. In the WD+RG systems, in particular, most of the RG companions have evolved to helium/carbon-oxygen WDs in the spin-down phase before the SN Ia explosions. In such a case, we do not expect any prominent signature of the companion immediately before and after the explosion. We also compare our new models with the recent stringent constraints on the unseen progenitors of SNe Ia such as SN 2011fe.

*Subject headings:* binaries: close — stars: winds, outflows — supernovae: individual (SN 2011fe)— supernovae: general

## 1. INTRODUCTION

Type Ia supernovae (SNe Ia) play important roles in astrophysics as a standard candle for measuring cosmological distances and as main production sites of iron group elements. It is commonly agreed that the exploding star is a mass-accreting carbon-oxygen (C+O) white dwarf (WD). However, it is not clarified yet whether the WD accretes H/He-rich matter from its binary companion [single degenerate (SD) scenario], or two C+O WDs merge [double degenerate (DD) scenario] (e.g., Hillebrandt & Niemeyer 2000; Nomoto et al. 2000).

Observations have provided the following constraints on the nature of companion stars. Some evidences support the SD model, such as the presence of circumstellar matter (CSM) (Patat et al. 2007; Sternberg et al. 2011; Foley et al. 2012) and detections of hydrogen in the circumstellar-interaction type SNe (Ia/IIn) like SN 2002ic (Hamuy et al. 2003) and PTF11kx (Dilday et al. 2012). On the other hand, there has been no direct indication of the presence of companions, e.g., (1) the lack of companion stars in the images of SN 2011fe (Li et al. 2011), some SN Ia remnants (SNRs) (Schaefer & Pagnotta 2012), SN 1572 (Tycho) (Kerzendorf et al. 2009) and SN 1006 (Kerzendorf et al. 2012), (2) the lack of ultraviolet (UV) excesses of early-time

light curves (Kasen 2010), and (3) the lack of hydrogen features in the spectra (Leonard 2007). Both (2) and (3) are expected from the collision between ejecta and a companion.

In particular, detailed observations of SN 2011fe in M101 require stringent constraints on the progenitor, i.e., Li et al. (2011) excluded the presence of a red-giant (RG), a helium star, or a main-sequence (MS) star of  $\gtrsim 3.5 M_{\odot}$ . Brown et al. (2012) further excluded a solar mass MS companion from an early UV observation with *Swift* because of no signature of shock interaction between ejecta and a companion.

The tightest constraints come from no signature of shock interaction with the companion. However, if the binary separation,  $a$ , is much larger than the companion radius,  $R$ , i.e.,  $a \gg R$ , the solid angle subtended by the companion would be much smaller, and so would be the effect of shock interaction. In their spin-down scenario, Justham (2011) and Di Stefano et al. (2011) argued that the donor star in the SD model might shrink rapidly before the WD explosion, because it exhausts its hydrogen-rich envelope before the SN Ia explosion during a long spin-down phase of the rapidly rotating, super-Chandrasekhar mass WD. In such a case, the companion star is much smaller than its Roche lobe, which reduces the shock signature. This also explains the lack of hydrogen in the spectra of SNe Ia and possibly the unseen companion in the SNR (Di Stefano & Kilic 2012). Hachisu et al. (2012) presented possible evolutionary routes to super-Chandrasekhar mass WDs in the WD+MS channel of the SD model. They also compared the spin-down time

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of WDs with the companion star’s MS lifetime and discussed their final states at explosions, although their main-focus was to explain the observed extremely luminous SNe Ia.

In this Letter, we apply our method in Hachisu et al. (2012) to WD+RG binaries, and calculate the WD mass distribution beyond the Chandrasekhar mass limit for both the WD+MS and WD+RG systems. We then estimate the brightness distribution of SNe Ia, assuming that the brightness depends on the WD mass. We further confirm that, in most of the WD+RG systems, the companion has evolved off from a RG to a helium (or C+O) WD before the SN Ia explosion and such a compact companion does not show any prominent shock signatures nor indications of hydrogen. In Section 2, we describe our basic assumptions and methods. Section 3 presents our numerical results. Section 4 discusses various perspectives on the progenitors of SNe Ia.

## 2. BINARY EVOLUTION BEYOND THE CHANDRASEKHAR MASS

Based on the SD model, we followed binary evolutions in which a WD accretes hydrogen-rich matter from its companion. There are two well studied evolutionary paths to SNe Ia, the WD+MS and WD+RG channels. Our basic assumptions in binary evolutions are essentially the same as those in Hachisu et al. (1999a,b, 2008a,b, 2012). Mass-accreting WDs blow optically thick winds if the mass transfer rate exceeds the critical rate,  $\dot{M}_{\text{cr}} = 6.68 \times 10^{-7} (M_{\text{WD}}/M_{\odot} - 0.445) M_{\odot} \text{ yr}^{-1}$  (Hachisu et al. 1996; Nomoto et al. 2007).

The WD winds collide with the secondary’s surface and strip off its surface layer. If the mass-stripping is efficient enough, the mass transfer rate is attenuated and the binary avoid the formation of a common envelope even for a rather massive secondary of  $\sim 4\text{--}6 M_{\odot}$ . Thus, the mass-stripping effect widens the donor mass range of SN Ia progenitors. We have incorporated the mass-stripping effect in the same way as in Hachisu et al. (2008a, 2012), i.e., the mass stripping rate  $\dot{M}_{\text{strip}}$  is proportional to the wind mass-loss rate  $\dot{M}_{\text{wind}}$  as  $\dot{M}_{\text{strip}} = c_1 \dot{M}_{\text{wind}}$ . In this study, we assume  $c_1 = 3$  as a lower representative value for the WD+MS system, because Hachisu & Kato (2003a,b) found that  $c_1$  is between a few to 10 to reproduce the optical and X-ray light curve behaviors of some supersoft X-ray sources. If we adopt a larger value, we could have a more massive secondary. For the WD+RG systems,  $c_1$  is calculated from Equation (21) of Hachisu et al. (1999a).

Mass-accreting WDs spin up because of angular momentum gain from the accreted matter (Langer et al. 2000; Uenishi et al. 2003; Piersanti et al. 2003). If the WD rotates rigidly, its mass can only slightly exceed the Chandrasekhar mass of no rotation,  $M_{\text{Ch}} = 1.46(Y_e/0.5)^2 M_{\odot}$  with electron mole number  $Y_e$ . If the WD rotates differentially, however, its mass can significantly exceed  $M_{\text{Ch}}$  (e.g., Hachisu 1986). Yoon & Langer (2004) concluded that the WD increases its mass beyond  $M_{\text{Ch}}$  when the accretion rate to the WD is as high as  $\dot{M}_{\text{WD}} \gtrsim 10^{-7} M_{\odot} \text{ yr}^{-1}$ . They showed that the gradient of angular velocity is kept around the critical value for the dynamical shear instability and that this differential rotation law is strong enough to support WDs whose masses significantly exceed  $M_{\text{Ch}}$  (Yoon & Langer 2005). Piro (2008) showed that highly differential rotation may not be realized due to baroclinic instability. However, his stability condition is not a sufficient condition but just a necessary condition for instability, so that his conclusion is premature (see Hachisu et al. 2012).

In the present study, we simply assume that mass-accreting

TABLE 1  
WHITE DWARF MASS DISTRIBUTION OF TYPE IA  
SUPERNOVAE<sup>a</sup>

WD mass ( $M_{\odot}$ )	WD+MS <sup>b</sup> (%)	WD+RG <sup>c</sup> (%)	ellipticals <sup>d</sup> (%)	total (%)
1.38–1.5	48.2	41.1	19.8	44.8
1.5–1.6	13.7	22.7	6.7	17.9
1.6–1.7	13.6	14.0	2.0	13.8
1.7–1.8	9.6	10.0	0.5	9.8
1.8–1.9	8.2	6.2	0.0	7.2
1.9–2.0	2.9	3.7	0.0	3.3
2.0–2.1	1.8	1.6	0.0	1.7
2.1–2.2	1.3	0.8	0.0	1.1
2.2–2.3	0.7	0.0	0.0	0.4

<sup>a</sup> metallicity  $Z = 0.02$ , binary mass ratio distribution  $f(q) = 1$

<sup>b</sup>  $\nu_{\text{WD+MS}} = 0.0035 \text{ yr}^{-1}$  in our Galaxy

<sup>c</sup>  $\nu_{\text{WD+RG}} = 0.0031 \text{ yr}^{-1}$  in our Galaxy

<sup>d</sup>  $M_{2,0} < 1.2 M_{\odot}$  is assumed for elliptical galaxies

TABLE 2  
WD MASS VERSUS MAXIMUM  
LUMINOSITY DISTRIBUTION

WD mass ( $M_{\odot}$ )	ratio (%)	$\Delta m_{15}(B)$ (mag)	ratio <sup>a</sup> (%)
1.38–1.6	62.7	1.1–2.1	67.4
1.6–1.8	23.6	1.0–1.1	17.3
1.8–2.0	10.5	0.9–1.0	10.2
2.0–2.3	3.2	0.7–0.9	5.1

<sup>a</sup> taken from Blondin et al. (2012)

WDs are supported by the above differential rotation law and the mass can increase without carbon being fused at the center as long as  $\dot{M}_{\text{WD}} > 1 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$  ( $\equiv \dot{M}_b$ ). We assume that, when  $\dot{M}_{\text{WD}} < \dot{M}_b$ , hydrogen shell-burning occurs intermittently on the WD and the resultant nova outbursts eject a large part of the envelope mass (Hachisu & Kato 2001). As a result, the net growth rate of the WD mass is significantly reduced ( $\lesssim 10^{-8} M_{\odot} \text{ yr}^{-1}$ ). Then the timescale of angular momentum deposition to the WD core would become much longer than  $\sim 10^7 \text{ yr}$  and comparable to the timescale for the Eddington-Sweet meridional circulation ( $\sim 10^8 \text{ yr}$ ) to redistribute angular momentum. This redistribution causes a contraction of the WD core and its central density increases high enough to trigger an SN Ia explosion before the WD mass significantly increases. Thus, if the WD mass increases beyond  $1.38 M_{\odot}$ , we define the WD mass at the SN Ia explosion as the WD mass when the mass transfer rate drops to  $\dot{M}_b$ .

Figures 1 and 2 show the parameter regions that produce SNe Ia in the  $\log P - M_2$  (orbital period–companion mass) plane for the metallicity of  $Z = 0.02$ . We plot results for four initial WD masses of  $M_{\text{WD},0} = 1.1, 1.0, 0.9$ , and  $0.8 M_{\odot}$  because (1) no C+O WDs of  $M_{\text{WD},0} \gtrsim 1.1 M_{\odot}$  are expected for normal metallicity (Hachisu et al. 2012) and (2) the  $0.7 M_{\odot}$  region is too small for the WD+MS systems and none for the WD+RG systems. The WDs inside these SN Ia regions (labeled “initial”) will increase their masses from (a)  $M_{\text{WD}} = 1.1$ , (b) 1.0, (c) 0.9, and (d)  $0.8 M_{\odot}$  to  $M_{\text{WD}} = 1.38, 1.5, 1.6, \dots, 2.2 M_{\odot}$  ( $0.1 M_{\odot}$  step from outside to inside contours) and reach the regions labeled “final.” We stop the binary evolution when the mass transfer rate decreases to  $\dot{M}_b$ . Both the WD+MS and WD+RG systems can produce a super-

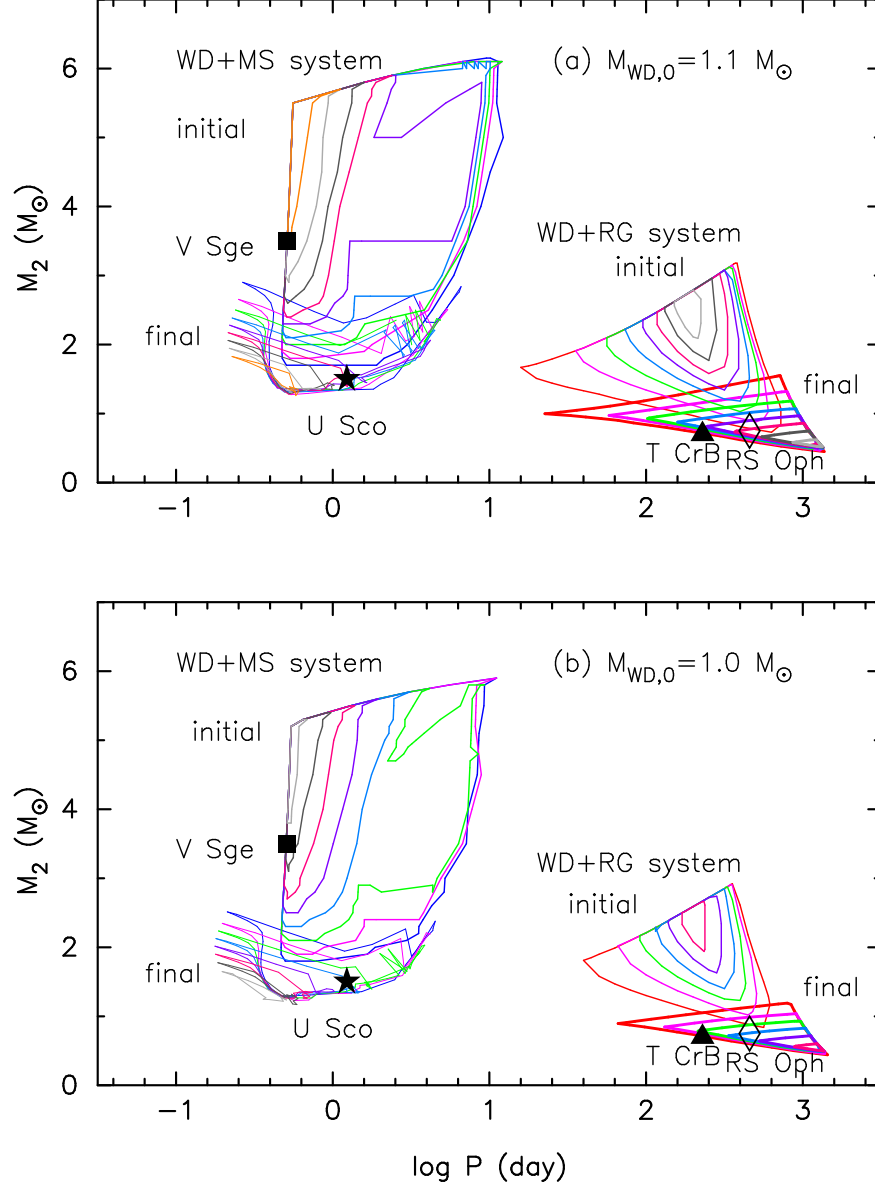


FIG. 1.— Regions producing SNe Ia with various initial WD masses are plotted in the  $\log P - M_2$  (orbital period – donor mass) plane both for the WD+MS system (*left*) and the WD+RG system (*right*). The initial system inside the region encircled by a solid line (labeled “initial”) is increasing its WD mass up to the mass of  $M_{WD} = 1.38, 1.5, 1.6, \dots, 2.1$ , and  $2.2 M_\odot$  (from outside to inside) and then reaches the regions labeled “final” when the WD stops growing in mass. Currently known positions of recurrent novae and supersoft X-ray sources are indicated by a star mark (★) for U Sco (e.g., Hachisu et al. 2000a), a filled square for V Sge (Hachisu & Kato 2003b), a filled triangle for T CrB (e.g., Belczyński & Mikołajewska 1998), and an open diamond for RS Oph (e.g., Brandi et al. 2006).

Chandrasekhar mass WD up to  $\sim 2 M_\odot$ .

### 3. DISTRIBUTION OF WD MASSES AT SN Ia EXPLOSION

The SN Ia regions for different initial WD masses,  $M_{WD,0} = 0.7, 0.8, 0.9, 1.0$ , and  $1.1 M_\odot$  are calculated both for the WD+MS and WD+RG systems. We then estimate the SN Ia birth rate in our Galaxy as  $\nu_{WD+MS} = 0.0035 \text{ yr}^{-1}$  and  $\nu_{WD+RG} = 0.0031 \text{ yr}^{-1}$  for the constant star formation rate. Here we assume the initial distribution of binaries given by Equation (1) of Iben & Tutukov (1984), i.e.,  $\nu = 0.2 \int f(q) dq \int dM / M^{2.5} \int d \log a \text{ yr}^{-1}$  and the distribution of mass ratio  $f(q) = 1$ .

We also estimate the delay time distribution (DTD) of SNe Ia as shown in Figure 3a, where the delay time ( $t_{\text{delay}}$ ) is the elapsed time from binary birth to explosion. The spin-down time of WDs is not included. The computa-

tional method is the same as that in Hachisu et al. (2008b). These values are normalized to fit the DTD at 11 Gyr (Mannucci et al. 2005). Our DTD shows a featureless power law ( $\propto t_{\text{delay}}^{-1}$ ) from 0.1 to 12 Gyr, which is consistent with Totani et al.’s (2008) observation. The present results are essentially the same as our previous results by Hachisu et al. (2008b) in which we assume that the WD explodes as an SN Ia at  $M_{WD} = 1.38 M_\odot$ . In general, the WD+MS systems consist of a young population of SNe Ia corresponding to short delay times ( $t_{\text{delay}} \lesssim 1 \text{ Gyr}$ ) and the WD+RG systems an old population of long delay times ( $t_{\text{delay}} \gtrsim 1 \text{ Gyr}$ ).

We further calculate the distribution of the WD masses at SN Ia explosions as in Table 1 and in Figure 3b–d. We also plot the number ratio of the WDs for the WD+RG systems with the initial companion masses of  $M_{2,0} < 1.2 M_\odot$ , which are expected to occur in elliptical galaxies (see Hachisu et al.

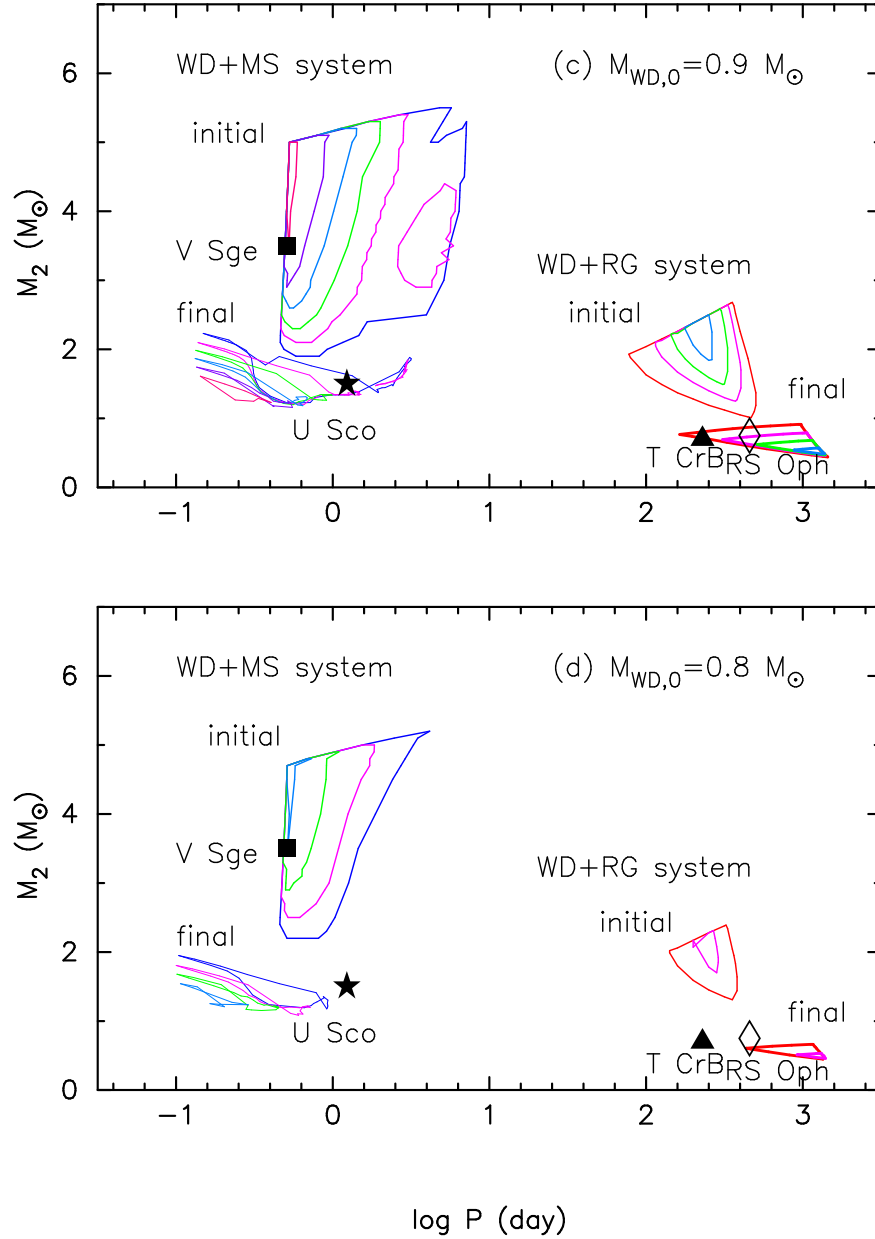


FIG. 2.— Continued from Figure 1.

2010). It is clear that the WD mass distribution in ellipticals is confined into a narrower range of  $1.38\text{--}1.6 M_{\odot}$  than in late type galaxies.

#### 4. DISCUSSION

##### 4.1. Spin-down time and final fate of WDs

After the mass transfer rate drops to  $\dot{M}_b$ , the WD stops growing in mass. There are three characteristic mass ranges for the final evolution of WDs toward an SN Ia explosion (see Hachisu et al. 2012, for detail).

(1) In the extremely massive case, the differentially rotating WD explodes as an SN Ia soon after the WD mass exceeds  $2.4 M_{\odot}$  owing to a secular instability. This is not the present case, because it happens for  $M_{\text{WD},0} \gtrsim 1.2 M_{\odot}$  in only low metallicity environments.

(2) For the mid-mass range of  $M_{\text{WD}} = 1.5\text{--}2.4 M_{\odot}$ , the WD is differentially rotating and its mass exceeds the maximum mass for rigid rotation. As angular momentum in the WD core

is lost or redistributed toward rigid rotation, the WD core contracts until its central density and temperature become high enough to ignite carbon. Thus the timescale of contraction until the SN explosion is  $\sim 10^8$  yr due to angular momentum transport by the Eddington-Sweet meridional circulation.

As for the other angular momentum transport mechanisms, Ilkov & Soker (2011) showed that magneto-dipole radiation leads to spin-down in a typical timescale of  $\sim 10^8\text{--}10^9$  yr for  $M_{\text{WD}} \gtrsim 1.6 M_{\odot}$  when the magnetic field of the WD is as weak as  $\sim 10^6$  G. They also showed that the  $r$ -mode instability is not significant in spinning-down WDs. Thus, we here assume that the Eddington-Sweet meridional circulation is the most effective process for spin-down.

(3) For the lower mass range of  $M_{\text{WD}} = 1.38\text{--}1.5 M_{\odot}$ , the WD can be supported by rigid rotation while it exceeds the critical mass of non-rotating WDs for carbon ignition. Thus, the WD contracts with the spin-down timescale, which is determined by angular momentum loss from the WD and thus

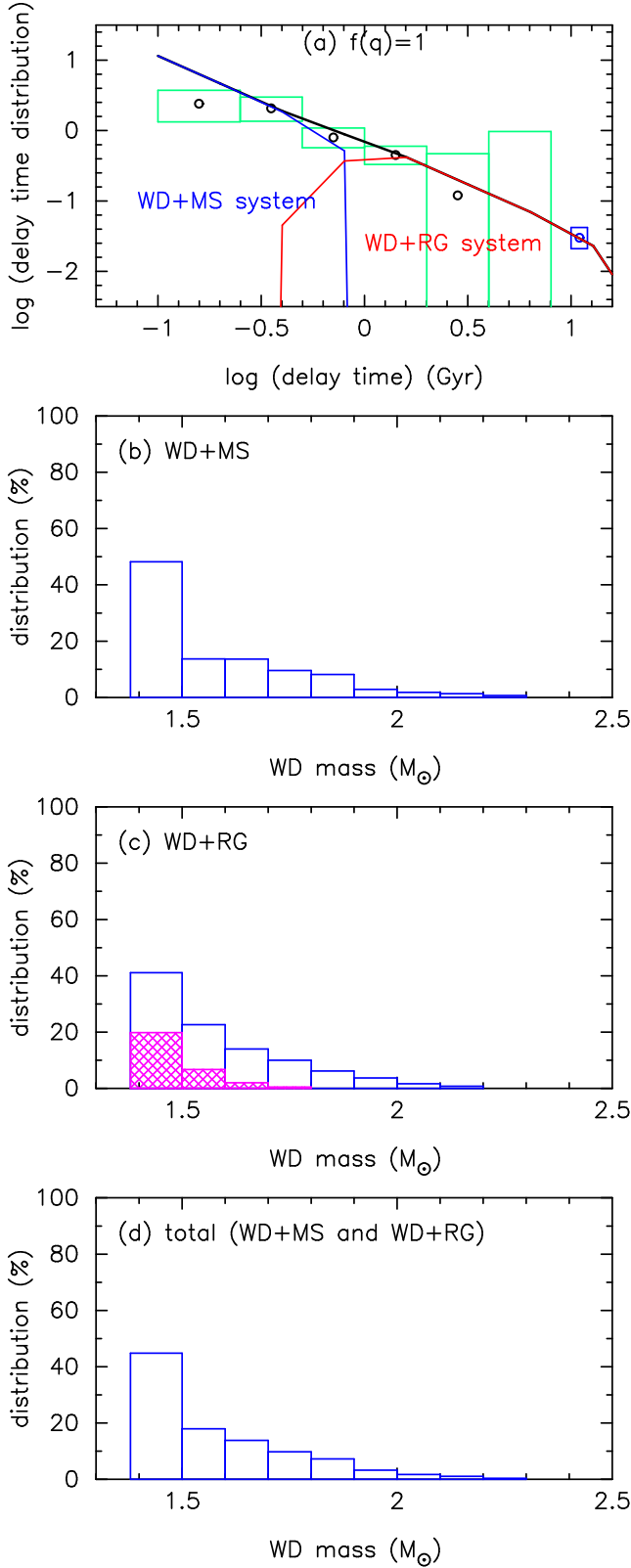


FIG. 3.— (a) Delay time distribution (DTD) for our WD+MS (blue solid), WD+RG (red solid) models, and the total (black solid) of them. The ordinate is the DTD in units of per century and per  $10^{10} L_{K_{\odot}}$ . Open circles with an open box are the observational DTD taken from Totani et al. (2008) (for  $< 10$  Gyr) and Mannucci et al. (2005) (at 11 Gyr). Each open box indicates a  $1\sigma$  error of each measurement. (b) Number ratio of the WD masses for the WD+MS systems. (c) Same as (b), but for the WD+RG systems. Hatched regions indicate the contribution of  $M_{2,0} < 1.2 M_{\odot}$ , corresponding to elliptical galaxies. (d) Same as (b), but for the total of WD+MS and WD+RG systems.

depends on the strength of the magnetic field of the WD. The final fate of the WD depends on the spin-down time as we discuss below. It may take more than  $\sim 10^9$  yr for weak magnetic fields of  $\sim 10^6$  G (Ilkov & Soker 2011).

If the spin-down time is not much longer than  $\sim 10^9$  yr, the compressional heating due to the spin-down would dominate the radiative cooling of the WD (see Equation (7) of Nomoto 1982). Because the spin-down time is not unique, its variation causes a variety of thermal state of WD cores when carbon ignites at the center. This would lead to a variation of the carbon ignition density and thus a variation of  $^{56}\text{Ni}$  mass and brightness of SNe Ia even for the same WD mass.

If the spin-down time is much longer than  $\sim 10^9$  yr, on the other hand, the central density at the carbon ignition could become high enough to induce collapse (Nomoto & Kondo 1991). This collapse produces a quite little amount of  $^{56}\text{Ni}$  as  $\sim 10^{-3} M_{\odot}$  (Wanajo et al. 2009), which might correspond to a faint transient.

#### 4.2. Final fate of WD+MS systems

In most of the WD+MS systems, the companion remains to be an MS (central hydrogen burning) star until the “final” stage of evolution. As shown in Figures 1 and 2, these systems have an orbital period shorter than  $\sim 1$  day and a companion mass smaller than  $\sim 2 M_{\odot}$ . This type of pre-supernova binaries satisfy the constraint on SN 2011fe posed by Li et al. (2011),  $M_{\text{MS}} < 3.5 M_{\odot}$ .

If  $M_{\text{WD}} = 1.5\text{--}2.4 M_{\odot}$  and the spin-down time ( $\sim 10^8$  yr) is shorter than the MS lifetime of the companion, the WD explodes before the companion evolves off the main-sequence. In most of these cases, the companion’s mass further satisfies the condition of  $M_{\text{MS}} \lesssim 1 M_{\odot}$  posed by Brown et al. (2012) on the SNR 2011fe, because the companion’s mass further decreases from the “final” mass in Figures 1 and 2 by the amount of roughly  $\Delta M \sim 10^{-8} M_{\odot} \text{ yr}^{-1} \times 10^8 \text{ yr} \sim 1 M_{\odot}$ , which is transferred to the WD and ejected by nova outbursts. On the other hand, if  $M_{\text{WD}} = 1.38\text{--}1.5 M_{\odot}$  and the spin-down time ( $\sim 10^9$  yr) is longer than the MS lifetime of the companion, the companion becomes a helium WD and CSM has disappeared. Such a case might correspond to the case of no CSM like SN 2011fe (Patat et al. 2011).

As already discussed in our previous paper (Hachisu et al. 2008a), the mass-stripping effect produces a large amount of CSM, say, a few to several solar masses ( $\approx$  initial mass minus final mass, as seen in Figures 1 and 2). If the spin-down time is short enough, or if the WD is forced to be rigidly rotating during accretion due to strong magnetic fields, the WD may explode in the CSM. Then we may observe the interaction between the ejecta and the CSM like in SNe Ia/IIn.

#### 4.3. Final fate of WD+RG systems

In the WD+RG systems, after the mass transfer rate drops to  $\dot{M}_b$ , the companion RG further evolves and finally becomes a helium (or C+O) WD in a timescale of  $< 10^8$  yr. This timescale is shorter than the spin-down time in both the mid-mass range ( $1.5 M_{\odot} < M_{\text{WD}} < 2.4 M_{\odot}$ :  $\sim 10^8$  yr for the Eddington-Sweet circulation) and lower mass range ( $1.38 M_{\odot} < M_{\text{WD}} < 1.5 M_{\odot}$ :  $\sim 10^9$  yr for the magneto-dipole radiation) WDs. The companion RG has already evolved to a WD when the primary WD explodes as an SN Ia. Therefore, the immediate progenitor is a wide binary consisting of WD+WD for all the cases. These immediate progenitors sat-

isfy all the constraints mentioned in Section 1. It might correspond to SN 2011fe, which shows no CSM. It also explains the lack of hydrogen in the spectra of SNe Ia and possibly the unseen companions of SN 1572 (Tycho) (Kerzendorf et al. 2009), SN 1006 (Kerzendorf et al. 2012), and SNR 0509-67.5 (Schaefer & Pagnotta 2012).

In the above discussion, we assumed that the spin-down time is  $\gtrsim 10^8$ – $10^9$  yr. However, if the spin-down time is short enough, or if the WD is forced to be rigidly rotating during accretion, the WD may explode before the companion evolves off the red-giant or asymptotic giant branch. Then we may observe the interaction between the ejecta and the CSM like in Kepler’s SNR (Chiotellis et al. 2012) and in PTF11kx (Dilday et al. 2012).

#### 4.4. Variation of Type Ia supernovae

In our progenitor models, various types of SNe Ia can be explained as follows: Normal SNe Ia correspond to the lower mass range of WDs,  $1.38 M_\odot < M_{\text{WD}} \lesssim 1.5 M_\odot$  (or  $\lesssim 1.6 M_\odot$ ). The brightness variation can be explained as a variety of spin-down time. The brighter group of SNe Ia such as SN 1991T correspond to the mid-mass range of WDs,  $M_{\text{WD}} \gtrsim 1.5 M_\odot$  (or  $\gtrsim 1.6 M_\odot$ ). We think that for these brighter SNe Ia, the brightness variation stems mainly from a variation of WD mass. Here we set the border between the normal and brighter SNe at about  $1.5 M_\odot$ . However, it depends on the timescale of the Eddington-Sweet circulation which may become longer near rigid rotation. Therefore, this border could be as massive as  $M_{\text{WD}} \sim 1.6 M_\odot$ .

Now we explain the luminosity distribution of SNe Ia with our model. In the observation, peak brightnesses of SNe Ia depend monotonically on the  $\Delta m_{15}(B)$ , where  $\Delta m_{15}(B)$  is the  $B$ -magnitude decay from the maximum in 15 days. Table 2 compares the WD mass distribution in our model with the observational  $\Delta m_{15}(B)$  distribution (Blondin et al. 2012). For the brighter group of SNe Ia ( $M_{\text{WD}} \gtrsim 1.6 M_\odot$ ), the distribution of  $\Delta m_{15}(B)$  is in good agreement with the WD mass distribution. This may be a support for our theoretical expectation that the brightness of SNe Ia is determined mainly by the WD mass because the thermal state is similar among various WD cores due to its relatively short spin-down time. For the fainter group of SNe Ia ( $M_{\text{WD}} \lesssim 1.6 M_\odot$ ), however, the brightness of SNe Ia depends not only on the WD mass but also on the spin-down time as mentioned in the previous subsection.

To summarize, we examined the final fate of the two progenitor models of SNe Ia, the WD+MS and WD+RG systems. A major part of the WD+MS systems reasonably satisfy the stringent constraints on SN 2011fe in M101. Most cases of the WD+RG systems satisfy even more stringent constraints on SNR 0509-67.5 posed by Schaefer & Pagnotta (2012).

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